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Strategic Blue-Green Communication Filters

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Final Report

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I. INTRODUCTION

This report describes the work that was performed under Contract N00014-78-C-0526, Strategic Blue-Green Communication Filters. The project began as an effort to construct narrowband, wide-field-of-view, large-aperture, plastic, birefringent filters suitable for blue-green communications. During the course of the study we investigated the use of crystalline materials in addition to plastic films, and we studied filter design theory in order to find designs more suitable to the blue-green system requirements. In addition, we constructed a quartz, 2Å filter for the 1981 SLCAIR experiment.

In this report we have included an introduction to the principles of narrowband, wide-field-of-view, birefringent filters. This section is included since the subject matter is not readily available except piecemeal in technical journals. Section III is a discussion of the materials which were considered during this study. It contains subsections devoted to crystals, plastics and analog elements, respectively. A class of new lossless filter designs is described in Section IV. These designs are expected to provide a basis for high-transmission filters in the future. The operational SLCAIR-81 filter is described in Section V. It was part of the successful experiment which demonstrated communication to the USN Dolphin, a research submarine. Finally, in Section VI we describe the non-vignetting filter design which was discovered during this study. It represents a significant throughput advantage for crystal filters used in non-imaging applications.

Many people have contributed to this project. Ralph Reeves, as always, was invaluable in suggesting practical ideas for handling the plastic films. In addition he constructed the laboratory stretching unit and the case for the SLCAIR-81 quartz filter. Harry Ramsey made the initial plastic film laminates and was the authority on cementing and scattering in the materials. He tuned and assembled the SLCAIR-81 filter. George Joki and Tony Bower spent many hours aligning and laminating plastic films to investigate the practical problems which were encountered. In addition, Tony worked diligently in our attempt to polish the PET films. Finally, the theoretical advances in lossless filter design and the principle of non-vignetting were due to many hours of discussion between Alan Title and Bill Rosenberg.

II. FILTER PRINCIPLES

This section reviews the types and capabilities of birefringent filters. The general operating principles of Lyot (perfect polarizers), and Solc (no internal polarizers) filters are introduced. The technique for tuning each filter type is presented. Field of view of birefringent filters is discusssed and is compared to Fabry-Perot and interference filters. The transmission and throughput advantage of birefringent filters are shown.

The essential principle involved in birefringent filters is that light originating in a single polarization state can be made to interfere with itself. In a birefringent element this is accomplished by decomposing the input wave into two orthogonal polarization components, delaying one component relative to the other, and then recombining the components to effect interference. This process is illustrated in Figure 1. The light is forced into a single polarization state by the entrance polarizer. By placing this polarizer at 45° to the fast and slow axes of the birefringent crystal, two components of

equal amplitude are created. A relative delay is introduced between these components by the difference in propagation velocity along these two axes. Finally, the exit polarizer forces the two waves, the ordinary and the extra-ordinary, to recombine and, hence, interfere.

An analogous situation occurs in a Michelson interferometer as shown in Figure 2. Here the two paths are created by a 50:50 beamsplitter and the relative delay is introduced by the path length difference between the two arms. Interference is effected by recombining the two beams with the beam splitter as shown. This analogy can be carried further by using polarizing beam splitters which create orthogonally polarized waves in the two paths just as in the birefringent element. Practical filter elements have been made this way and are very similar to birefringent elements (Title and Ramsey, 1980).

The effect of placing either a birefringent element or a Michelson interfero-meter in an optical path is to transmit at some wavelengths and to reject at others. In particular, the output due to white light input is a channel spectrum with alternating light and dark bands in the spectrum. Mathemati-cally, the spectral transfer function of such an element is

$$T(\lambda) = \cos^2(\frac{\pi \Delta d}{\lambda}) \qquad (1)$$

with Δ, the birefringence, d, the thickness of the element and λ, the wave-length. The birefringence is the difference between the ordinary and extra-ordinary indices of refraction, n_o and n_e, respectively. A thick plate produces a channel spectrum of many thin bands closely spaced while a thin plate produces a channel spectrum of fewer but wider bands.

An alternative perspective on birefringent systems is impulse response analysis borrowed from electrical engineering (Bracewell, 1965). Here, the Fourier transform duality between time and spectral domains is used to characterize birefringent filters. As in electrical filter theory the spec-tral transfer function of an optical filter is the square magnitude of the Fourier transform of its impulse response. For a birefringent element, or Michelson interferometer, the impulse response is especially easy to derive. As shown in Figure 3, an impulse passing through the entrance polarizer is split and travels along the fast and slow axes of the element. These two impulses are separated in time by the delay of the element. Finally, the exit polarizer creates two identically polarized impulses as the output. The orthogonally polarized impulses which are rejected by the exit polarizer represent the power which is lost in the dark bands of the channel spectrum. The impulse response of the element is thus a pair of impulses separated in time by
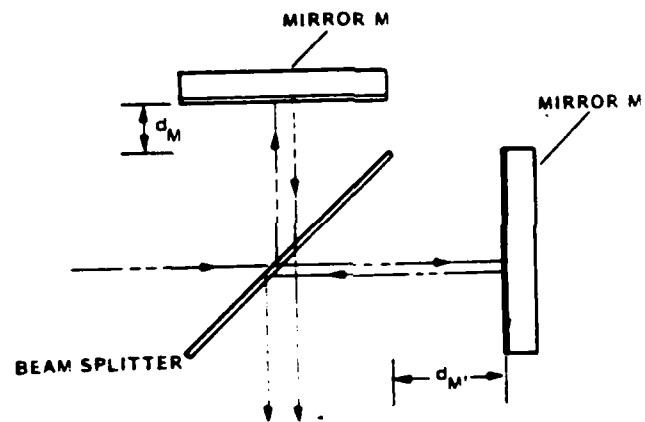
$$\Delta t = \frac{d}{c} (n_o - n_e) \qquad (2)$$

in which c is the vacuum speed of light. Specifically this may be written as
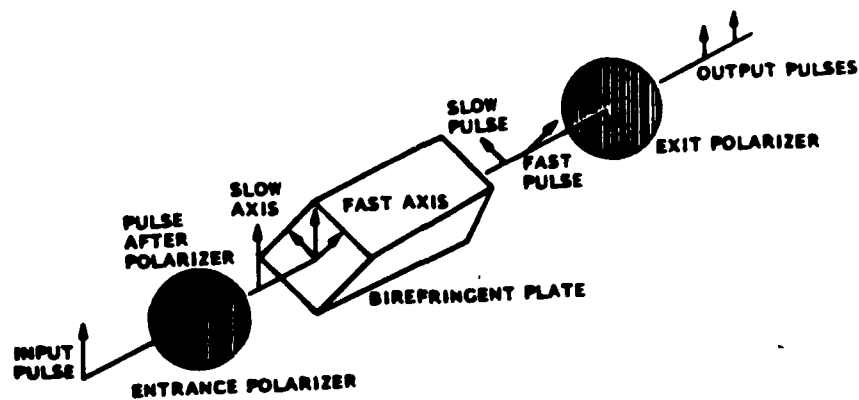
$$h(t) = \frac{1}{2} \delta(t - \frac{n_o d}{c}) + \frac{1}{2} \delta(t - \frac{n_e d}{c}) \qquad (3)$$

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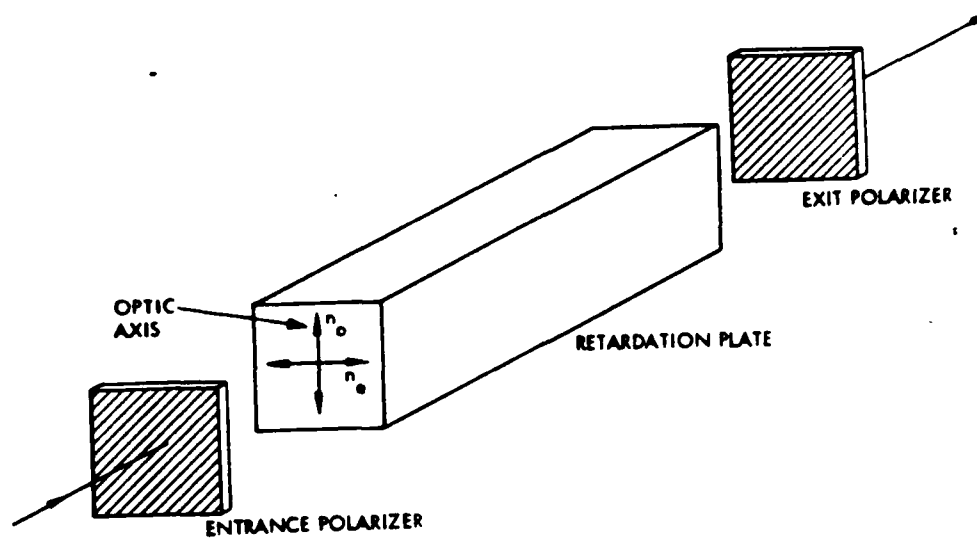
1. Simple birefringent element.

2. Michelson interferometer element.

3. Pulse propagation through a simple element.

Since the absolute time of arrival of the impulses is not important in specifying the square magnitude of the transform, (3) is usually written as

$$h(t) = \frac{1}{2}\, \delta(t + \frac{\Delta t}{2}) + \frac{1}{2}\, \delta(t - \frac{\Delta t}{2}) \qquad , \qquad (4)$$

In equations (3) and (4), $\delta(t-a)$ is the Dirac delta function representing an impulse at time a. As is well known, equation (1) is the square magnitude of the Fourier transform of equation (3) or (4).

The simple birefringent elements described above can be combined in several different ways to produce useful optical filters. The types of interest here, Lyot and Solc, differ in the use of polarizers between successive elements in a filter. In this section we will review these filter types, but will only reference the details and derivations of many of the properties of the filters.

Lyot filters are the simplest of the filter types (Lyot, 1933). In a Lyot filter, as shown in Figure 4, simple elements whose lengths are in the ratios $1:2:4:8:\ldots 2^n$ are cascaded. Each element has an entrance and exit polarizer. The exit polarizer of each element serves as the entrance polarizer of the next. Each element, in effect, serves as a blocking filter for the next thickest element, doubling the spectral spacing between transmission maxima while changing the narrow pass band response only slightly. The overall effect of a four-element Lyot filter is shown in Figure 5. The transmission profile for each element is shown along with the overall profile for the entire filter. Since the elements are in series the overall profile is the product of the individual spectral responses. The impulse response for the entire filter is the convolution of the individual responses, a uniformly weighted impulse sequence.

The transmission profile for a Lyot filter with n elements is

$$T(\lambda) = \frac{1}{4^n} \frac{\sin^2(\frac{2^n \pi c \Delta t}{\lambda})}{\sin^2(\frac{\pi c \Delta t}{\lambda})} \qquad (5)$$

in which Δt is the time delay of the shortest element. For a transmission maximum at λ_0, the bandwidth (full width at half maximum) is approximately

$$\text{FWHM} = .88 \frac{\lambda_0^2}{2^n c \Delta t} \qquad (6)$$

while the free spectral range is

$$\text{FSR} = \frac{\lambda_0^2}{c \Delta t} \qquad (7)$$

Consequently the finesse, the ratio of free spectral range to bandwidth, of Lyot filters is

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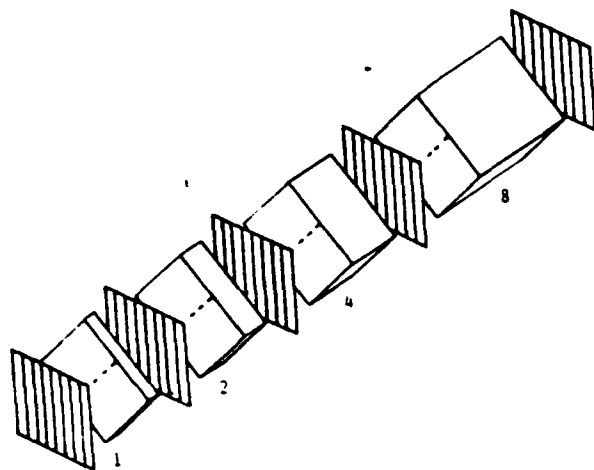
4. Lyot filter with four elements.

5. Transmission versus frequency for the components of a Lyot filter (A, B, C, D) and the transmission through successive stages of the cascade (E, F, G)

$$F = 1.13 \ 2^n \tag{8}$$

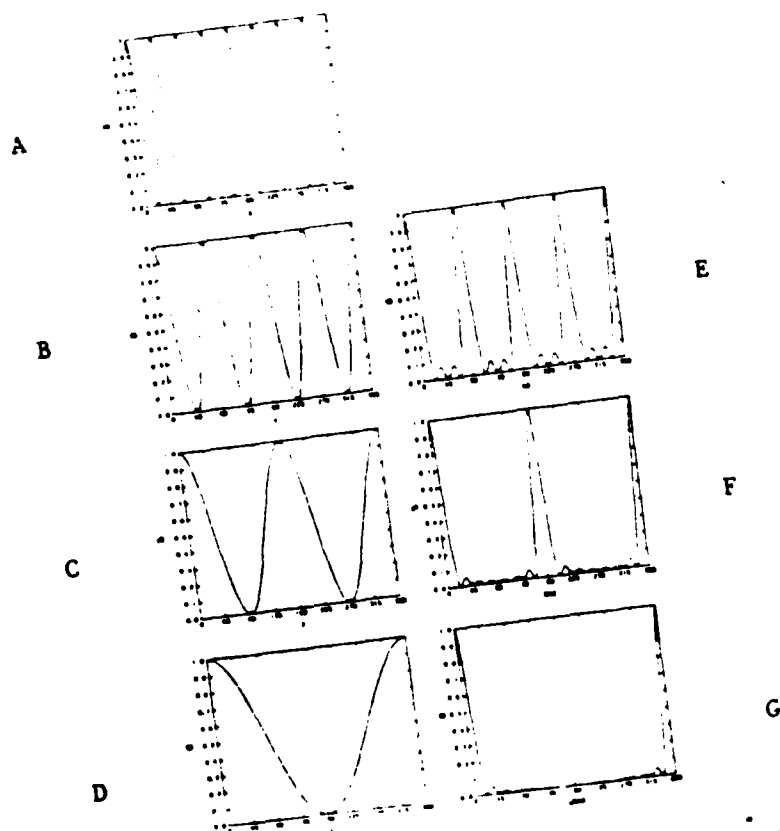Practical filters have been built with a FWHM of .05 Å at λ5000 Å and a finesse of 290. The height of the first sidelobe, the largest secondary maximum, relative to the peak transmission, of a Lyot filter is approximately .045, or -13 db.

There are many possible variations of the basic Lyot filter. The most well known is the contrast element Lyot in which one additional element is added to the filter (Schoolman, 1973). This element, instead of being twice the thickness of the longest element is, instead, approximately equal to the second longest element. Its purpose is to reduce the heights of the sidelobes and thereby increase the signal-to-noise, or contrast, in the filter transmission. Other variations include other modifications of the 1:2:4.... length ratios and deviations from having all the polarizers parallel.

By using contrast elements, the transmission spectral response may be varied somewhat from the pure Lyot response. Unfortunately, the freedom to specify spectral response is limited. Ammann and Chang (1965) describe a method for synthesizing arbitrary transmission functions but it is of more academic than practical interest. The theoretical transmission can be very low and the large number of polarizers limits the actual transmission even more.

Ivan Solc (1965) showed that it is possible to construct birefringent filters without any intermediate polarizers. The original Solc filters were very simple to describe, but have been very difficult to understand. They came in two forms, as shown in Figure 6, the fan filter and the folded filter. In a fan filter, n identical, unit length, birefringent plates are stacked as in a fanned deck of playing cards. The orientations of the plates are:

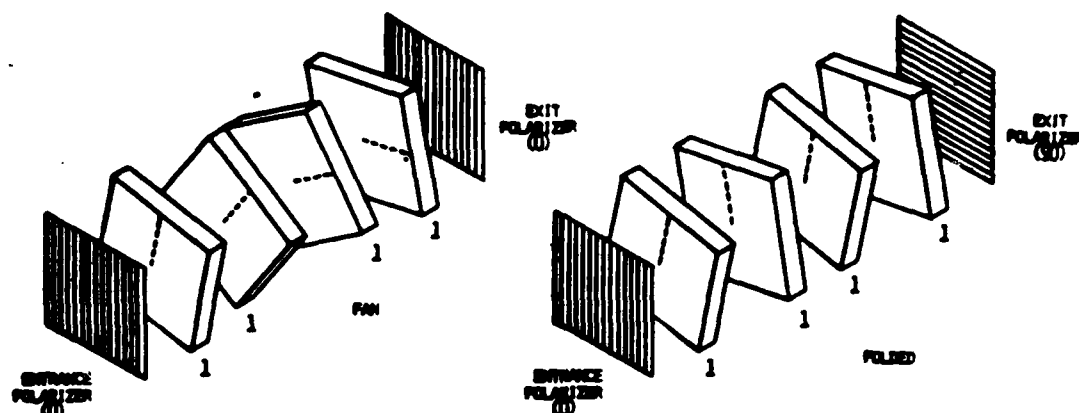$$\alpha, \ 3\alpha, \ 5\alpha, \ ...., \ (2n-1)\alpha \tag{9}$$

where $\alpha = 45°/n$. The orientations are symmetric around $45°$ and distributed regularly through the quadrant. Thus a four-plate filter would have its plates oriented at $11.25°$, $33.75°$, $56.25°$, and $78.75°$. For the fan filter the entrance and exit polarizers are oriented parallel at $0°$.

The folded filter is simpler in design. Its plates are oriented, alternately, at $+\alpha$ and $-\alpha$. A four-plate folded filter would have its plates oriented at $11.25°$, $-11.25°$, $11.25°$, and $-11.25°$. The entrance polarizer is at $0°$, but the exit polarizer is at $90°$.

The spectral transmissions of the fan and folded Solc filters are equivalent. They both have the same profile, although they are shifted from each other by half the free spectral range. In Figure 7, the transmission profiles of the four-plate fan and folded filters are shown. In general Evans (1958) has shown that the transmission profile of an n plate Solc filter is:

$$T(\lambda) = \left[\frac{\sin n\chi}{\sin \chi} \cos \chi \tan \alpha \right]^2 \tag{10}$$

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ENTRANCE POLARIZER (II)

EXIT POLARIZER (II)

FAN

1
1
1
1

ENTRANCE POLARIZER (II)

EXIT POLARIZER (⊥)

FOLDED

1
1
1
1

6. Solc fan and folded four-element filter configurations

FWHM: 70.52 FINESSE: 5.1 SIDELOBE: 4.29E-02
IN-BAND: 1.60E-01 OUT-OF-BAND: 5.02E-02 S/N: 3.18

PLATES
RET ANG
1   1   11.25
2   1 -11.25
3   1   11.25
4   1 -11.25

FOLDED FILTER

FWHM: 70.52 FINESSE: 5.1 SIDELOBE: 4.29E-02
IN-BAND: 1.60E-01 OUT-OF-BAND: 5.02E-02 S/N: 3.18

PLATES
RET ANG
1   1   11.25
2   1   33.75
3   1   56.25
4   1   78.75

FAN FILTER
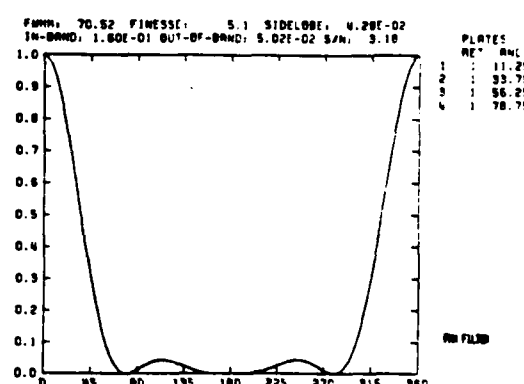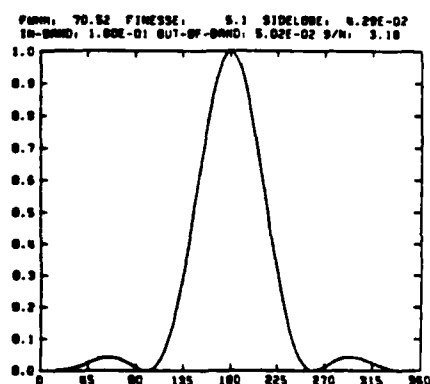
7. Transmission versus frequency of four-element fan and folded filters.

in which

$$\cos \chi = \cos \frac{\pi c \Delta t}{\lambda} \cos \alpha$$

and α, as before, is $45^{o}/n$.

In Figure 8 we compare Solc fan and Lyot filters. Notice that for filters using the same total crystal thickness the Lyot filter has slightly lower secondary maxima (side lobes) for comparable bandwidths. This was observed soon after Solc invented these filters and was thought to be a significant disadvantage. This objection, however, was due largely to a lack of understanding as to how the Solc filters really worked.

Harris, Ammann, and Chang (1964) made a significant contribution to the development of Solc filters by applying the impulse response concept to these filters. As in the analysis of partial polarizing filters the impulse response must be considered to be a vector quantity. Unlike the partial polarizing networks, however, in which the convenient coordinate system remains constant throughout the network, for Solc filters a better choice is one in which the coordinate system rotates with the crystal plates. In particular, at each intermediate stage the convenient coordinate axes are the fast and slow axes of the preceeding crystal plate. By combining this idea with a mathematical technique developed by Pegis for the synthesis of multilayer dielectric interference filters, Harris et al demonstrated a general synthesis technique for Solc filters. That is, given any discrete time, finite impulse response, there is a set of crystal plate orientation angles which synthesizes such a filter. Thus, for example, with the plate orientation angles:

$$8.4^{o}, \ 18.9^{o}, \ 31.4^{o}, \ 45.0^{o}, \ 58.6^{o}, \ 71.1^{o}, \ 81.6^{o}$$

the corresponding filter would exactly duplicate the transmission profile of a Lyot filter. Schiffman and Young (1968) using the Harris procedure, demonstrated that more interesting filters could be built. They built a Dolph-Chebyshev minimum sidelobe filter. Figure 9 shows various seven-plate filter configurations and their spectral responses.

It is difficult to compare these filters directly since there are several attributes involved. The standard Lyot filter, or the Lyot filter with contrast element, while less general in its spectral characteristics requires far fewer elements than an equivalent Solc filter. The Solc filter, however, uses only two polarizers and therefore can achieve higher transmission in practice since even good polarizers have some losses.

One of the major advantages of birefringent filters over interference filters is the ease with which they can be tuned. There are, in fact, three basic tuning techniques which can be used in birefringent systems. The direct method, similar to air spaced Fabry-Perot tunable filters, is actually to change the birefringent optical path length. An indirect method which uses quarter wave plate analyzers as optical compensators for each retardation plate is more practical, however. Finally, electro-optical techniques which adjust the retardation of certain crystals can be used.

For the direct method some mechanism for adjusting the birefringent optical path length must be employed. Temperature control has often been used. The
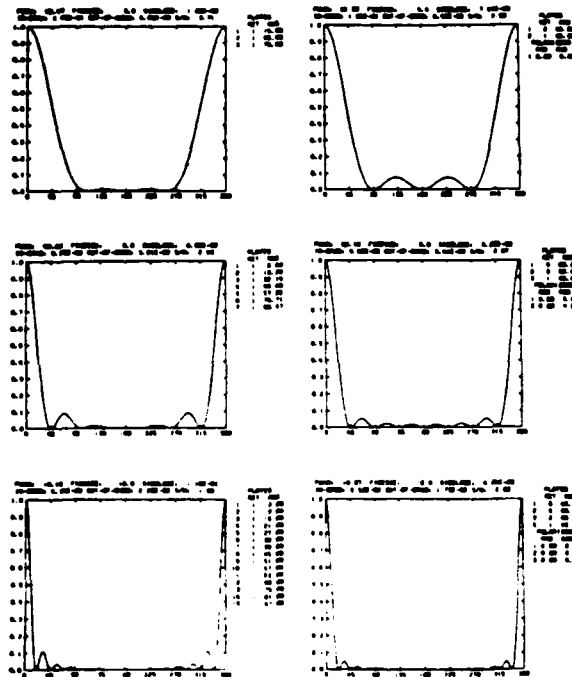
8. Transmission versus frequency of equal length Solc and Lyot filters.
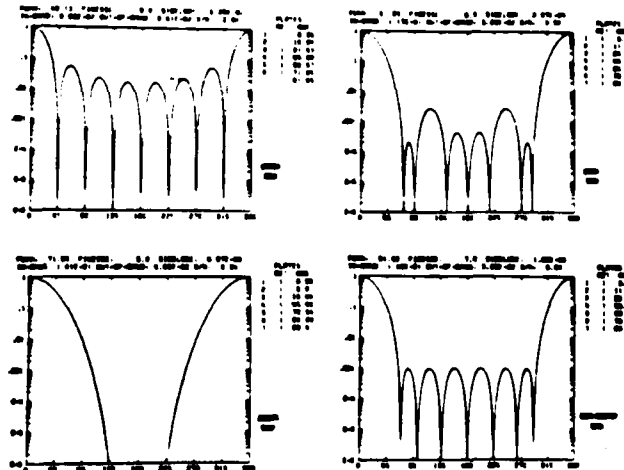
9. Transmission versus frequency for seven-element Solc filters with uniform, mean taper, binomial, and Dolph-Chebyshev apodizations.

dominant effect of temperature change is a change in birefringence, although there is a physical length change also. For quartz the result is approximately a shift of -.5 Å per degree Celcius while for calcite the shift is -.3 Å per degree Celcius in the visible. The length can also be changed mechanically by using wedge shaped retardation plates in pairs. By sliding one plate in and out with respect to its mate, the physical thickness is changed. For imaging systems such a change in the optical path is undesirable, but for some applications it works well. A Solc filter with wedge tuning has been built and works well as an order separation filter for a spectrograph.

By far the best tuning method is to use quarter wave plate analyzers (Title and Rosenberg, 1979a). The basic configuration is shown in Figure 10. A quarter wave plate, achromatic over the wavelength range of interest, is mounted immediately following the retardation plate. Tuning is then accomplished by rotation of the exit polarizer. Mathematically this procedure can be shown to work, but intuitively it is difficult to understand. Briefly, the output of the retardation plate is elliptically polarized light, whose ellipticity is a function of wavelength,

$$\epsilon = \text{ellipticity} = \frac{\text{horizontal axis}}{\text{vertical axis}} = \tan \frac{\pi d}{\lambda} \quad . \quad - n_o) \quad (11)$$

The quarter wave plate, as a polarization analyzer, transforms elliptically polarized light into a linearly polarized wave whose orientation is a function of the ellipticity,

$$\theta = \tan^{-1} \epsilon . \qquad (12)$$

The orientation as a function of wavelength becomes

$$\theta = \frac{\pi d}{\lambda} (n_e - n_o) - n\pi . \qquad (13)$$

At $\theta = 0$, vertical, the natural wavelength, λ_o, is selected. The tuning relationship is, therefore,

$$\theta = \pi d (n_e - n_o)(\frac{1}{\lambda} - \frac{1}{\lambda_o}) \qquad (14)$$

Rotation by half a revolution tunes through a free spectral range of the element. The sensitivity of the wavelength setting to angular orientation errors actually decreases for the longer, narrow bandwidth elements. This property makes tuning to within a small fraction of the filter bandwidth very practical.

For practical filters it is desirable to avoid rotating the polarizer as in Figure 10 since that would require rotating the following retardation plate and therefore all the subsequent elements. This may be avoided by introducing
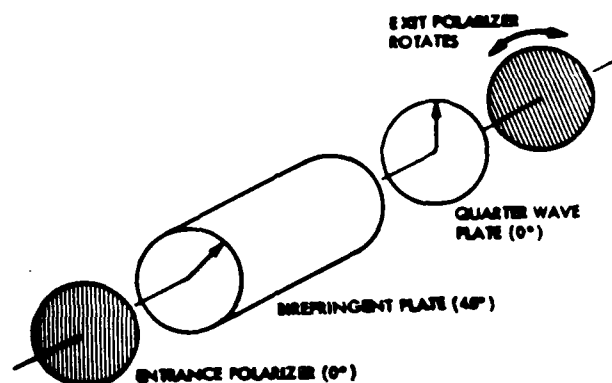
10. Simple quarter-wave tuning element.
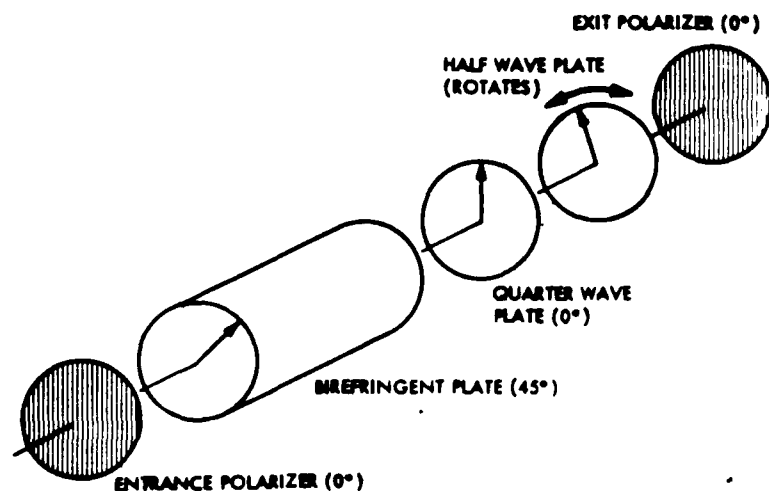
11. Practical quarter-wave: half-wave tuning element

12. General tuning element suitable for Solc filters.

a rotatable half wave plate before the exit polarizer as shown in Figure 11.
The polarizers and retardation plates remain fixed which improves the imaging
performance and only the half wave plates rotate.

Solc filters retain both orthogonal polarization components from element to
element. The tuning sections, therefore, must tune both polarization states
simultaneously. The configurations shown in Figures 10 and 11 do not maintain
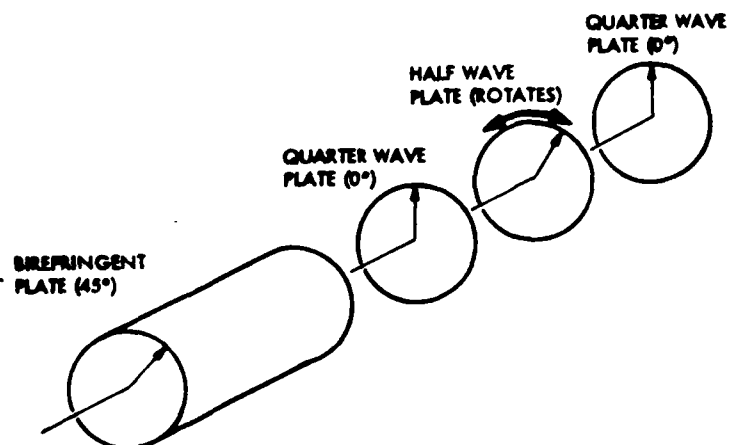the proper phase relationship between the orthogonal polarizations and must be
modified in order to tune more general filters. In Figure 12 a general tuning
configuration is shown. Notice that an additional, fixed, quarter wave plate
has been added after the rotating half wave plate. The extra quarter wave is
just the retardation needed to correct the phase difference between the
orthogonal polarizations.

Electro-optic tuning is also possible, but has not yet been utilized in prac-
tical filter systems. There are two principles which can be used for electro-
optic tuning. The first is to change the retardation of a birefringent element
in response to an electric field. Materials such as ADP or KDP are used for
this purpose and may either be used as the retardation element itself or as an
additional tuning section following the main element. The other type of
electro-optic tuning is a replacement for the rotating half wave plate in the
tuning elements of Figures 11 and 12. Liquid crystal elements may be used as
electrically controlled half wave plates, but have not yet been used in tunable
birefringent filters.

The advantage of electrical tuning is that there are no moving parts in the
optical path. Unfortunately, the electro-optic materials which have been used
to date all require either transparent electrodes in the optical path or large
electric voltages. The problems arise because transparent electrodes aren't
really quite transparent enough. If several layers are included in a filter the
losses combine to reduce the transmission significantly. If, alternatively,
transverse electric fields are used for apertures of several centimeters the
voltages required become excessive. Many liquid crystals, for example, require
fields of about 1 volt/micron.

Other than tunability, the great advantage of birefringent filters is the
large field of view possible (Title and Rosenberg, 1979b). Unlike interfer-
ence filters in which the off axis behavior is isotropic, uniaxial birefrin-
gent crystals have a strong azimuthal dependence. In particular, the fringe
pattern of a uniaxial birefringent element is a series of hyperbolic isochromes
rather than the circular pattern of an interference filter. Moreover, the
change in retardation actually changes sign between consecutive quadrants of
the fringe pattern. For rays at 0° azimuth, with respect to the optic axis,
the retardation decreases with incidence angle as:

$$\Delta(i,0^{\circ}) = \Delta_o \left[1 - \frac{\sin^2 i}{2n_o^2} \right] \qquad (15)$$

while in the next quadrant, at an azimuth of 90°, the retardation increases as

$$\Delta(i,90^{\circ}) = \Delta_o \left[1 + \frac{\sin^2 i}{2n_o n_e} \right] \qquad (16)$$

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At arbitrary azimuth, θ, the retardation variation is

$$\Delta = \Delta_o \left[1 - \frac{\sin^2 i}{2n_o} \left(\cos^2\theta - \frac{n_o}{n_e} \sin^2\theta\right)\right] \qquad (17)$$

The azimuthal behavior is the key to making widefield elements. If two plates are combined with their optic axes crossed then the positive increase in retardation of one plate will be offset by the negative change in retardation of the other plate. Lyot has shown that there are two ways to exploit this behavior. The first is to use two identical plates of the same uniaxial material. Then, to avoid just having the plates cancel and produce a wide field zero retardation, a half wave plate must be placed between the two crossed elements. Such a configuration is shown in Figure 13. The spectral capability of the wide field element is limited by the half wave plate. If it is achromatic then so will be the wide field element (Title, 1975).

Another type of wide field element can be made by crossing two retardation plates, one being uniaxial positive and the other, uniaxial negative. Again the positive and negative azimuthal quadrants will cancel, but now the fast and slow axes will line up from one crystal to the next. Remember that for a uniaxial positive crystal the fast axis coincides with the optic axis while for a uniaxial negative cystal they are orthogonal. A wide field element may, therefore, be made from a combination such as quartz and calcite.

The negative and positive retardation changes, as given by equations (18) and (19), are not exactly equal. There is, therefore, still some limitation to the field of a wide field element. To second order the retardation of a wide field combination is:

$$\Delta(i) = \Delta_o \left[1 - \frac{\sin^2 i}{4n_o{}^2} \frac{(n_e - n_o)}{n_e}\right] \qquad (18)$$

The variation of transmitted wavelength as a function of incident angle is, therefore,

$$\frac{\delta\lambda}{\lambda_o} = - \frac{\sin^2 i}{4n_o{}^2} \left(\frac{n_e - n_o}{n_e}\right) \qquad (19)$$

This should be compared with the variation for interference filters, which is

$$\frac{\delta\lambda}{\lambda_o} = - \frac{\sin^2 i}{2n^2} \qquad (20)$$

in which n is the index of the spacer layer. The field advantage of the wide field birefringent element results from the factor

$$\frac{n_e - n_o}{2n_e} \qquad (21)$$

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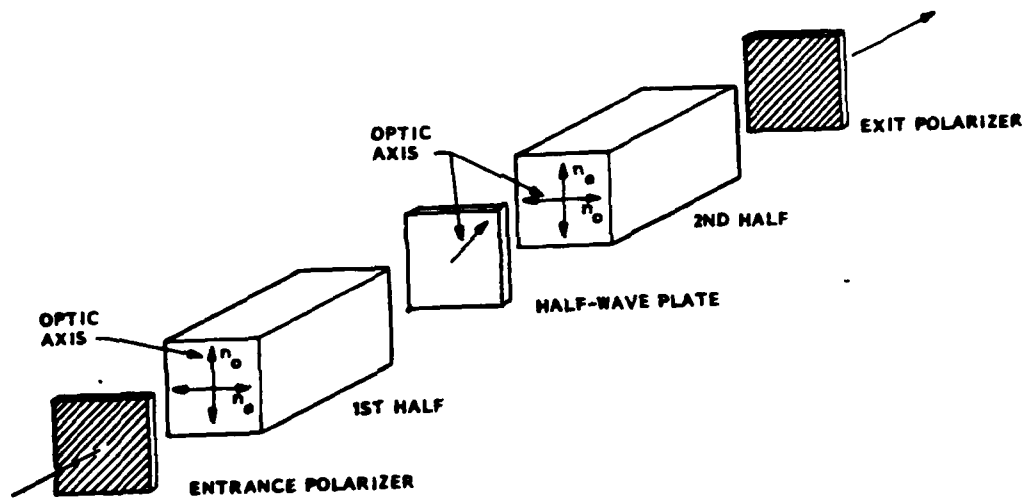
13. Wide field birefringent element.
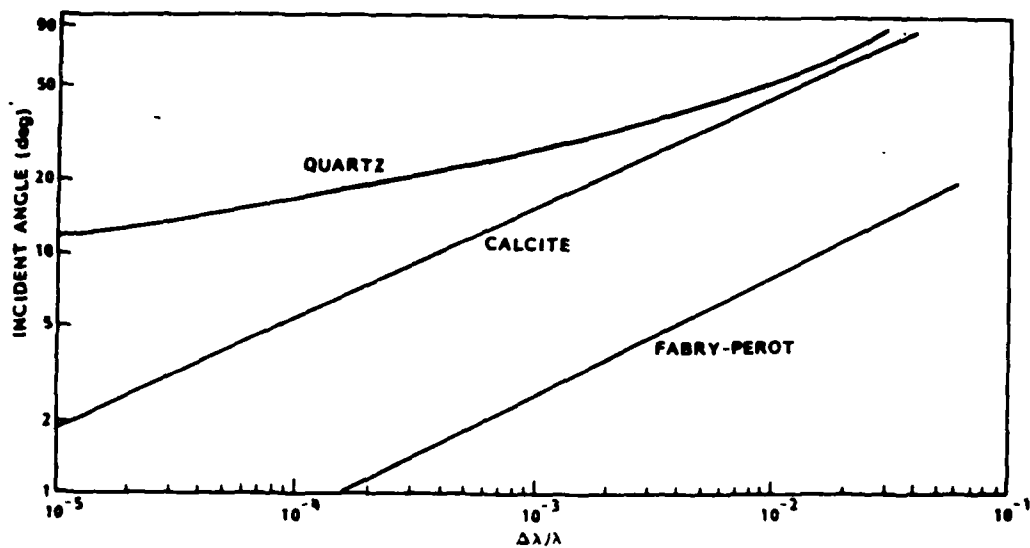
14. Off axis wavelength shift for wide field birefringent and interference filters.
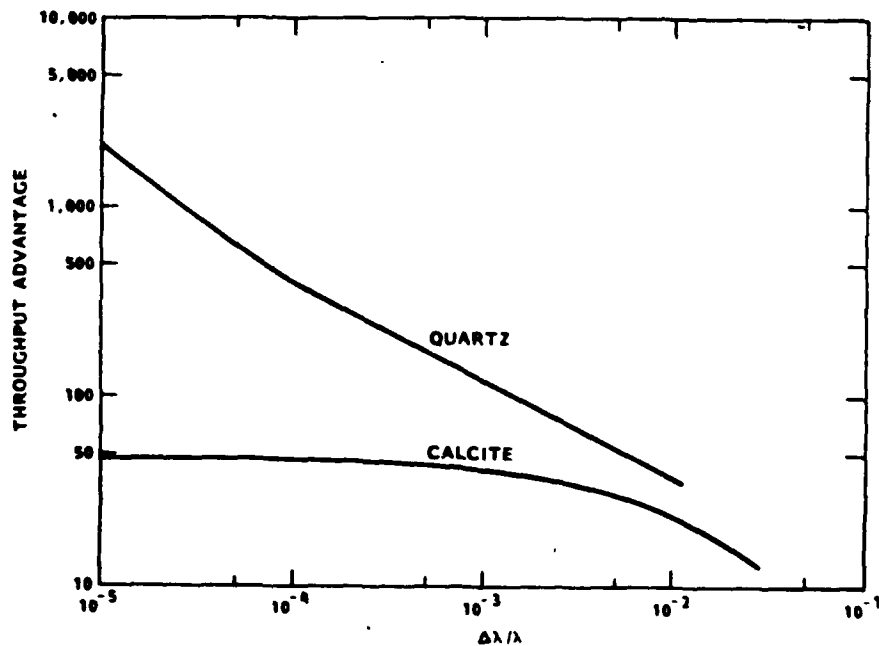
15. Throughput advantage of wide field birefringent filters.

For quartz this factor is .003 and for calcite it is -.058 resulting in large field advantages for birefringent elements. For very small birefringences the second order approximations are not sufficient and more exact computations are necessary. The results of such exact computations are shown in Figure 14 for elements operating at $\lambda5000$ Å. The incident angle corresponding to the relative wavelength tolerance, $\delta\lambda/\lambda$, is shown for quartz, calcite, and an air spaced Fabry-Perot interference filter.

For any filter system the question always asked is, "How much light can be accepted?" This encompasses a variety of factors, but results in an objective basis for comparison between filter systems. The acceptance of any system can always be increased by using a larger aperture filter, so any comparison among types must assume similar apertures. Achievable aperture limitations may then be considered separately. What remains, therefore, is the solid acceptance angle over which the filter operates and the losses in the filter itself.

Birefringent filters operate over a large solid angle as implied by the field of view discussion in Section 5. The throughput advantage relative to Fabry-Perot interference filters is shown in Figure 15 for filters constructed of quartz and calcite. In practice this advantage is a factor of 50 to 200.

The throughput advantage of birefringent systems is somewhat diminished by internal losses in the polarizers. These need not be serious losses, however, if efficient polarizers are used. An unavoidable loss is due to the entrance polarizer. This means that 50% of the incident light is lost immediately unless the source is polarized. A Lyot filter with a finesse of 250 requires nine polarizers. If their transmission, in polarized light, is 95%, the overall attenuation is a factor of 63%. The overall transmission of such a filter would then be 32% in unpolarized light. A modified Solc hybrid design using only three polarizers could transmit 43% in unpolarized light.

In the visible spectrum, where sheet polarizers are readily available, the Lyot designs are practical. Transmissions of about 30% are therefore realistic. For the infrared or ultraviolet the hybrid Solc filters become more attractive and will then yield transmissions of about 40%. The overall throughput advantage of birefringent filters, relative to ideal interference filters is therefore a factor of 15 to 80 in unpolarized light or 30 to 160 in polarized light.

III. FILTER MATERIALS

In this project we considered several types of materials and construction techniques for large-aperture filters. The three main areas in which we showed interest are conventional crystals, plastic films and glass Michelson analog elements. We also considered the possible use of liquid crystals, particularly the hematic form, but did not investigate it extensively. Since advanced material development was outside the scope of this project, we concentrated our efforts on commercially-available materials and simple extensions or modifications of them.

A. Crystals

Natural and cultured crystals have been the traditional materials for birefringent filters. In particular quartz and calcite have been used in

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filters at Lockheed and elsewhere. For this project we considered sapphire, magnesium flouride and KDP, in addition to quartz and calcite. These are all uniaxial birefringent crystals which are potentially suitable as field-widened retardation plates.

There are several criteria by which these crystals may be compared. Ultimately the most important factor is availability of optical-grade material in sizes compatible with the large aperture requirements of the DARPA-NAVY Strategic Laser Communication (SLC) program. A secondary factor is degree of difficulty of optical fabrication. For one crystal, KDP, a final factor is environmental stability since it is water soluble.

Availability considerations mandate the use of cultured crystal material rather than natural crystals. Even though some excellent natural quartz crystals continue to be mined, their availability is always uncertain. There is no consistent supply of large, optical-quality quartz crystals. The very best quality quartz crystals are natural crystals, but the only consistent supply of good to excellent crystals is cultured quartz.

Calcite is, therefore, not acceptable as a crystal material for SLC filter programs. Natural calcite rarely occurs in single crystals exceeding 3 cm aperture and its quality is highly variable. To date, unfortunately, efforts to grow cultured calcite have not been at all successful. Growth rates are approximately 1 to 3 mm per month.

Cultured crystals of 1 cm are considered large. Since the growth process is hydrothermal, like quartz, it would be expected that the quartz growth tech-nology would be transferable to calcite. It appears, however, that there are problems specific to calcite which require large research and development investments before production becomes possible. The development of an acceptable quartz growth technology required a large government and industrial commitment in order to transform a feasible concept into a reliable commercial process. There is no reason to believe that a similar commitment to calcite technology would not also be successful, but in the absence of a compelling commercial or national security motivation, such an investment is unlikely.

Calcite, additionally, has two other drawbacks. The first is its softness. Calcite is 3 on the Mohs Scale of hardness which is undesirably soft. It is more difficult to grind and polish a soft material than a hard one. The other problem with calcite is its birefringence. With a birefringence of .17 it has been the crystal of choice for narrowband solar astronomy filters. As described in the previous section, however, a high-birefringence material has an inherently smaller field of view than a low-birefringence candidate. For a 2Å to 3Å filter, calcite would yield only an 8° to 9° field of view compared to 20° to 25° half angle for quartz.

Crystal quartz has been and will continue to be an excellent choice for wide-field filters in the 2Å - 100Å bandwidth region. Availability is not an issue since there are several commercial suppliers of optical grade cultured quartz crystals, or stones, as they are known. We have found the most suitable of these suppliers to be Sawyer Research Products in Eastlake, Ohio. They routinely grow large crystals, known as Sandia stones, of excellent optical quality. These crystals are grown hydrothermally from a seed whose dimensions are approximately 2 mm x 2.5 mm x 300 mm. The optic axis, known as the c-axis

or z-axis, is initially in the 2 mm direction. Crystal growth is anisotropic with no growth in the 300 mm direction, the y-axis. Growth in the z-direction is slightly faster than in the x-direction, producing crystals about 75 mm high in the x-direction, 100 mm wide in the z-direction, and 300 mm long in the y-direction. A crystal this size takes approximately 180 days to grow. By extending the growth time, larger crystals, up to perhaps 150 mm in the z-direction, are possible.

For field-widened birefringent filters, we normally use x-cut slices with the optic axis parallel to the top and bottom surfaces. Present cultured quartz technology is, therefore, consistent with apertures of 100 mm to perhaps 150 mm diameter. As we will discuss in a subsequent section, it is also consistent with non-vignetting square apertures of that width.

The birefringence of quartz is .009, which is low. This means that narrow-bandwidth filters such as 2Å to 3Å are undesirably thick (100 mm to 150 mm) but that they have good fields of view. In fact, since the Lyot filter design requires a combination of thick plates and thin plates, the birefringence of quartz is just barely small enough to allow grinding and polishing of the thinnest plates.

The last characteristic of quartz which makes it nearly ideal for birefringent filters is its hardness. It has a hardness of 7 on the Mohs scale. This is comparable to most glasses and is, therefore, compatible with the fabrication technology common to most optical finishing. It is hard enough to take a good optical surface but not so hard as to be difficult to grind.

We also considered sapphire as a candidate crystal. Recent advances in sapphire crystal growth technology have made it possible to specify moderate size components. In particular, Crystal System, Inc., in Salem, Massachusetts has a technique for cooling a melt sufficiently precisely to grow cylindrical sapphire crystal ingots approximately 200 mm diameter and 200 mm long. These boules, while nominally single crystals, have some microstructure to them very similar to crystal twinning. Refinements in the growth technology have reduced this effect and should be capable of further reduction in the near future. It is difficult to estimate potential size limitations though 150 mm of usable diameter seems realistic at present. Quite fortunately the preferred growth orientation is with the optic or c-axis perpendicular to the cylindrical axis of the boule. This means that retardation plates may be sliced from the boule just like salami.

Sapphire has a birefringence of .008, just slightly less than quartz. A filter of sapphire would have approximately the same length as a comparable quartz filter. Additionally, however, sapphire is a negative uniaxial crystal. While this does not affect its operation as a birefringent filter element material, it does allow an interesting combination with quartz. Usually a wide-field element is a sandwich construction. Two crystal retardation plates have a half wave plate interposed. The two plates are orthogonal to each other in order to cancel the azimuthal variation of a uniaxial crystal while the half wave plate rotates the plane of polarization in order to make the element additive. With a combination of a positive uniaxial crystal, such as quartz, and a negative uniaxial crystal, such as sapphire, the wide field effect can be realized without the intermediate half wave plate.

We considered the use of such quartz-sapphire combinations and investigated several samples of Crystal Systems sapphire. It was felt, however, that the saving of one half wave plate per element was not sufficient to justify the expense associated with sapphire plates. Because of relative immaturity of the sapphire growth technology, the price of optical grade sapphire is higher than that of quartz. Additionally, because sapphire is a much harder material (Mohs 9), the fabrication costs of slicing, grinding and polishing are correspondingly higher. The use of two different materials also introduces imbalances due to different thermal properties. Manufacturers of filters involving both quartz and calcite elements have found this annoying even though they did not combine both crystals in the same element. The problem is expected to be even more severe in a wide-field construction in which retardation tolerances are critical.

The other crystal material which was considered briefly is potassium di-hydrogen phosphate (KDP). We visited Interactive Radiation (Inrad) in Northvale, New Jersey, to observe crystal growing conditions and to discuss crystal processing. KDP is water soluble which is the best and worst characteristic simultaneously. Becuase it grows from a water solution at standard laboratory temperatures and pressure, it is extremely easy to grow even in large crystals. We saw crystals measuring approximately 30 cm x 30 cm x 90 cm and are told that 45 cm x 45 cm x 150 cm should be practical. The bad news is that since the crystals are so soluble they must be environmentally sealed in use. It would be possible to fabricate an entire filter and then seal it. The suppliers such as Inrad prefer sealing each plate individually which would be a considerable burden. Even though the material is relatively soft, its solubility makes grinding and polishing operations expensive because of the extra care required.

We did not pursue KDP although its size and availability are attractive. Its solubility was viewed as being prohibitive in the context of this study.

B. Plastics

The initial goal of this study was to investigate oriented polymer films as birefringent filter element material. For many years, at Lockheed and else-where, oriented plastic film has been used to make zero order quarter and half wave plates. At .025 mm or less, a sheet of plastic film is much thinner than is possible to grind and polish from crystalline materials. In particular, biaxially-stretched cellophane was used in several early filters and uniaxial poly (vinyl alcohol), PVA, has been used more recently. At Lockheed, we have used oriented PVA as zero order waveplates or, in Pancharatnam-type combinations, as achromatic plates.

Unfortunately, plastic film's major advantage, its thinness, is also its major weakness as the primary retardation material in a filter. While a single sheet might be one wave of retardation, a 2Å filter requires an element having 1300 waves of retardation. It is clearly impractical to laminate 1300 layers per element. In a prior project Harry Ramsey at Lockheed constructed a filter with as many as 50 laminants per element. This showed that the idea of multi-laminant elements was possible but also illustrated some of the limitations of the method. Specifically, Ramsey found that eight layers were as many as were feasible in a single unit. Beyond that there was too strong a possibility of edge delamination destroying the unit. Units of eight layers of PVA sand-

wiched between glass were used as substitutes for crytal plates in the assembly of the filter with a 50Å bandwidth.

It is clear that any practical lamination of plastic layers requires plastic film which is either significantly thicker or significantly more birefringent than the PVA film normally used. It was beyond the scope of this project to develop new polymers or to develop film casting equipment. We limited this study to commercially available films and considered the effect of uniaxial orientation on these films. Because of its high intrinsic birefringence we were mainly interested in poly (ethylene terephthalate), PET, a polyester known commercially as Mylar, Melinex, Petra, etc. We also continued to use PVA to investigate lamination technique because of its availability. Ethylene vinyl acetate was suggested during the study, and we considered polystyrene briefly.

Commercial plastic films of almost any polymer are usually biaxially oriented. That is, they are stretched either after or during their casting in such a way as to straighten out the long polymeric chains. This process tends to improve many mechanical properties of the plastic films. In particular, it tends to improve the tensile strength and also, in many cases, to increase the flexibility of the film. Thus, for example, unoriented or even uniaxial polystyrene is a fragile, brittle sheet. When stretched both lengthwise and crosswise, however, it becomes a flexible, strong film.

A biaxially oriented plastic film appears optically to be similar to a biaxial crystal. It is birefringent and has two optic axes. While it is suitable for use as a zero order wave plate, it will not work as part of a Lyot wide-field element. Thus, most commercial plastic film products were not satisfactory. Uniaxially oriented films, however, behave like uniaxial crystals. They have a single optic axis, in the direction of stretch, parallel to the surface of the film. Like uniaxial crystal plates they may be field widened by crossing two pieces with a half wave plate between. The first goal was, therefore, to obtain uniaxial plastic material.

Two approaches were used. The first method was to find ways to stretch plastic film ourselves, while the second was to find suppliers who would provide uniaxial material instead of the usual biaxial film. Both approaches were followed and in the end produced about the same results.

In order to consider stretching PET ourselves we needed to obtain a supply of unstretched or amorphous PET and a suitable device for uniaxial stretching. Obtaining amorphous PET proved to be more difficult then we at first had anticipated. The commercial plastics industry is a very competitive business with a lot of distrust and many trade secrets. Manufacturers are extremely hesitant about supplying material other than their standard product line. We were able, however, to obtain amorphous samples from several manufacturers.

We received samples of PETRA-A from Allied Chemical; Melinex from ICI Americas; Kodar PETG, an Eastman Chemical product prepared by Transilwrap; and several PET products from Teijin Ltd., a Japanese manufacturer. While these films are all poly (ethylene terephthalate), they all vary considerably in their optical properties. Some variation is due to slight differences in the polymerization which cause differences in the average chain lengths. Some variation is due to the casting process. The variables there are extrusion temperature, extrusion speed, surface polish of the casting drum, and perhaps others. Most

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variation, however, is due to additives which are introduced to the melt
during the casting process. These additives are introduced for a variety of
reasons and are considered to be highly proprietary. There is no way to find
out from the manufacturers just what they add to each of their product lines,
nor is there any way to obtain a sample with other than their usual additive
mix.

The first conclusion we reached is that the PET samples vary considerably in
their internal scattering. This is very important for two reasons. Scatter-
ing is a loss in the filter and reduces transmission. Even a little scatter-
ing in each layer of plastic film becomes quite significant in a stack several
centimeters thick. Another, insidious, result of scattering is depolariza-
tion. Scattered light loses its sense of polarization and tends to a polari-
zation state related only to the scattering angle. Since the filter action
depends critically on the propagation and interference of polarized light
through the filter, any depolarization is a degradation of performance. It
hurts both ways: the in-band light is reduced in transmission, and the out-
of-band leakage is increased.

Of the PET samples received, only the Teijin product had extremely low
scatter. It was as good as the optical grade PVA we have been using. From
discussions with Teijin representatives we conclude that it was pure PET with
no additives. Strangely, while the Teijin PET is produced under a license
from ICI Americas it is much clearer than the ICI amorphous material we
have. Again, the general reluctance to discuss additives or process vari-
ations makes it impossible to know the reasons. In general, however, the
Teijin, 5-mil amorphous PET is the best of all those we obtained. It is the
clearest and the most uniform. The next best sample was obtained from Allied
Chemical and was a 10-mil sample of PETRA-A. At the time Allied Chemical
was the only company making amorphous film which did not use it in its own
oriented product. This might have made communication easier. Unfortunately,
they had a contractual agreement with an undisclosed customer for whom they
were making the film, which they claimed proscribed disclosures.

Having obtained several small samples, some as short as 10 feet, the problem
became one of stretching the material. PET has a glass transition temperature
of about 70°C. At this temperature the material turns from the "glassy"
plastic to a more rubber-like form. At the glass transition temperature, it
suddenly becomes possible to stretch the film. Below that temperature it is
almost impossible to stretch and certainly impossible to do in anything like a
uniform manner. It is, therefore, necessary to have a special mechanism for
stretching PET.

The standard apparatus for orienting plastic film consists of two sets of
pinch rollers turning at different speeds. Material is stretched between
these two sets and flows through the mechanism in a continuous fashion. By
varying the overall speed, the differential speed, and the temperature of
the unit, the stretching process can be controlled. Marshall & Williams of
Providence, Rhode Island, is one of the leading suppliers of stretching equip-
ment for the plastic film industry. We visited them to discuss orientation of
PET in general and the use of a small test machine in their laboratory in
particular. This is a machine on which they rent time to people to try out
new techniques before setting up production equipment. It is ideally suited
for experiments such as ours. We felt that if we could obtain sufficient

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quantities of material and could define a set of operating parameters, then we would rent machine time at Marshall & Williams for a pilot run.

At the same time we realized how important it was to have a small unit for our own laboratory on which small samples could be stretched. Since no such units are commercially available at any reasonable cost, we chose to build our own. It is shown in the accompanying figure. It consists of a vertical chamber approximately five feet high and two feet wide which has double-pane viewing windows. A fixed holder grabs the single sheet of film at the top of the chamber, and a chain-driven movable holder grabs the bottom of the sheet. The temperature is monitored at several heights within the chamber and two sets of fans circulate the air to insure a uniform environment. The speed and the temperature may be varied within a wide range of values in order to determine the best operating point.

The results of the stretching experiments were disappointing. We found that the Teijin film which is so clear in its amorphous state became cloudy as soon as it was stretched. Although we varied the temperature from $70^{\circ}C$ to $100^{\circ}C$ and varied the stretching rates over a wide range, the results were always similar. The material began to scatter as it was stretched. Discussions with Teijin were, unfortunately, of little value. The conclusion was that as the long polymer chains straightened out they tended to form microcrystalline segments along their length. Several such chains would find themselves fitting side by side very nicely and become a tiny crystal. These crystalline portions tend to scatter causing the cloudy appearance. If anything, it might be the purity of the material which made it so prone to crystallize.

Allied Chemical's PETRA-A contains some additive which is intended to inhibit crystallization. It remained relatively clear during stretching although it started with some scatter in the amorphous state. We would say that the conclusion is that the proper choice of crystallization inhibitor could probably reduce the scatter to an insignificant level since the Teijin PET demonstrated that there are no intrinsic scattering centers in pure PET. Unfortunately, it was beyond our scope to have specialized film cast for us. As we will describe, the crystallization issue became relatively unimportant as we worked to improve uniformity.

The other method for obtaining uniaxial PET is to ask for it directly instead of asking for amorphous film and attempting to stretch it. We did this and obtained several samples from various manufacturers. The first sample of uniaxial PET we obtained was from T. M. Long of Somerville, New Jersey. He stretched some duPont Mylar sheets on a custom laboratory stretcher as a sample of his machinery. Interestingly, in retrospect, he was trying to demonstrate the uniformity of his orientation equipment rather than any superiority of the Mylar film. The film all had a strong striation pattern in it. The striations were mainly longitudinal and were quite pronounced with a spatial scale of several millimeters peak-to-peak.

We obtained other uniaxial samples made on commercial roller stretchers. One sample from duPont was interesting because it was an in-process section from a more extensive process. As we discussed, most commercial PET is biaxially oriented meaning it is stretched first in the longitudinal or machine direction and then in the transverse direction on a tentering frame. For a brief moment, as the material passes from the machine direction stretcher to the

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transverse direction stretcher, it is uniaxial. At this duPont plant the production manager cut off a piece at the beginning of a run before it got to the tentering frame. Since it was intended to be stretched approximately 3 to 1 in width, with a consequent thinning by about 3 to 1 in thickness (PET stretches at nearly constant volume), our sample was thicker than expected at about 20 mils).

From a duPont plant in Centerville, Ohio, we obtained another uniaxial Mylar sample. This sample came much later than the others and was actually stretched specially for us although not to any specifications by us. It was, however, uniaxially oriented on a machine specifically designed for PET. Similarly, ICI Ltd. in London, England, oriented a short roll of Melinex specifically for us. Again, they used one of their pilot plant machines and did not vary the operating parameters to optimize the process for our needs.

Another sample of uniaxial Melinex obtained indirectly from ICI Ltd. was very revealing of the limitations in the process. It seems that at about the same time as we were beginning to look for uniaxial PET so also was a group in the Polarizing and Retarder Films Division of Polaroid Corporation. They were not so particular about uniaxial material as we were but they did want uniform high-retardation material to serve as a polarization scrambler for white light. Even though orientation of PVA is their business, they did not attempt to orient PET themselves. This is due to the extreme difference in operating conditions for orientating PET from those for PVA. They settled on ICI as a supplier and contracted for some amount of uniaxial PET. After rejecting one or two attempts, they finally settled on a roll of transverse stretched PET. Polaroid trimmed the roll, keeping the center section and discarding the outer six inches along the edge. We were fortunate to be given one of these edge rolls and a sample of the central portion. Other than the tentering frame marks at the very edge, there is no difference between the edge roll and the central sample.

The interesting aspect of this ICI material is that it shows the same degree of nonuniformity although on a slightly better spatial scale, as our other samples and our own laboratory effort. The nominal retardation is about 20 waves with about a 1-wave peak-to-peak variation on a spatial scale of 1 cm. Similar variations were observed on the duPont samples, the other ICI samples and our own efforts. In retrospect we also concluded that a 5% variation was typical of the thin biaxial Mylar and the PVA zero order wave plate material. In zero order material, 5% is all but insignificant while for a twentieth order plate, 5% is a full wave. The conclusion is, therefore, that this variation is all but inevitable.

A final note on the orientation of PET concerns Allied Chemical's PETRA. One of their customers was American Can Company who was making uniaxial material for packaging. They used an entirely different technique which they described as being similar to calendaring. (Because of proprietary considerations they wouldn't reveal any more about the process.) Calendaring is a technique similar to rolling steel or pie crusts. Instead of pulling the material to orient it, it is rolled between polished steel rollers. Unfortunately, this technique does not appear to produce as good a film as the traditional stretching process.

The obvious question is, "What causes the nonuniformity?" Unfortunately we do not know for sure, but there are several possibilities. Most probably a combination of factors contribute. We find two sources of the nonuniformity. The first is a variation in the thickness of the amorphous film to start with. Second is the effect of nonuniform tension in the orientation process.

PET film is drum cast from the melt. The melted polymer is forced through a wide, thin mandril and as the jet is cooling, it lays on the surface of a polished metal drum. The drum is cooled and, as it rotates, it pulls the new film with it. At some point along the drum the plastic changes from a viscous fluid to a solid film. As with any fluid flow through a thin jet, small irregularities can develop leading to slight thickness variations in the film. These irregularities can either be along streamlines leading to longitudinal striation or they could be acoustic effects leading to transverse bars. Either way, there is little reason to expect absolute uniformity.

We found it difficult with our measurement capability to measure accurately the thickness of the material. One technique produced results which are very suggestive. We aluminized both sides of several samples of amorphous PET. Then, with the samples held like a drum head under slight radial tension, we examined the surfaces interferometrically. In each case, one surface was flat (presumably the drum surface), while the other was wavy. We suspect, therefore, that much of the nonuniformity in the oriented film is the result of variation in the amorphous precursor.

If the problem could be ascribed just to surface variations, it might be possible to solve it by surface treatment. We tried abrasive polishing, using various polishing materials, on the surfaces of oriented film. Although we used various samples we never found any real improvement. The conclusion is, therefore, that the birefringence variations are actually due to internal variations in the orientation of the polymer chains.

We would have liked to have been able to identify the birefringence variations as they developed in the orientation process and trace them back to nonuniformities in the amorphous material. This proved to be too difficult since the film changed too much during the orientation process. We tried printing grid patterns on the film before stretching in order to measure local variations but the results were inconclusive.

We were unable to distinguish slight thickness variations from birefringence variations. Since both result in optical path differences, standard transmission interferometric techniques could not separate the two effects. Ordinary mechanical thickness measurements were not accurate enough to use. There are now available surface profilometers which might be useful but these were not available to us during this study. We tried using ultrasonic thickness guages, but, again, they did not have enough sensitivity.

Our conclusion is that without the technical resources and cooperation of one of the commercial manufacturers of PET film, there is little chance to develop satisfactory plastic retardation material.

C. Glass Michelson Analogs

We will discuss only briefly the use of solid glass Michelson inerferometer elements as substitutes for birefringent crystals. The subject is discussed at length in Title and Ramsey (1980). We include it here because it presents an alternative to the standard materials discussed earlier in this section. Its use, however, is realistically limited to filters with bandwidths less than 1Å.

As described in Section II, a birefringent element is merely a combination of two optical paths corresponding to orthogonal polarization states. In a birefringent crystal, the two optical paths are actually physically coincident; two orthogonal (noninterfering) optical paths, one physical path. In a Michelson interferometer, as illustrated in Section II, a beam splitter creates two optical paths and, incidentally, two physical paths. If the beam splitter is polarizing, which is the easier arrangement, then the two optical paths are orthogonally polarized. In all spectral respects a Michelson interferometer with a polarizing beam splitter behaves just like a simple birefringent crystal element.

The field of view of a Michelson differs from that of a birefringent crystal element. Whereas the off-axis behavior of a uniaxial crystal depends critically on the ellipsoidal wavefronts of the extraordinary rays, the Michelson is governed only by geometry and Snell's law. Somewhat surprisingly, however, suitable choices of the indices of refraction in the two optical paths of the Michelson result in an extended field of view comparable to that of a field-widened birefringent element. The Michelson elements may, therefore, be used interchangeably with crystal birefringent elements. We have, in fact, constructed a 0.1Å bandwidth element and used it with a calcite birefringent filter.

For wide-bandwidth filters the Michelson offers no advantage. When the bandwidth desired is less than 1Å, however, the Michelson becomes superior to crystal elements. By comparison with quartz it takes up much less space. The comparison with calcite or almost any higher birefringence material is one of availability. Solid wide-field Michelson units are constructed entirely from commercially available optical glasses. While the assembly of a solid Michelson is a precision optical task, it is no more difficult than any current optical assembly operation.

IV. FILTER DESIGNS

It has often been noted that birefringent filters have poor on-axis transmission. Since their wide field of view provides a large throughput advantage over other interference filters, they are still very efficient as light collectors. It would be desirable, however, to improve the overall transmission. The first step is to identify the lossy components.

The main loss in birefringent filters is in the polarizers. Even ignoring the 50% loss represented by the entrance polarizer, the polarizers still account for more transmission loss than the rest of the filter. This is easy to understand when you realize that standard high-efficiency sheet polarizers only pass about 80% of the light in their pass direction. A filter with 8 polarizers would only transmit 17% of the light in the pass direction of the entrance polarizer or about 8% of unpolarized light.

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The other approach, and one we have considered seriously during this study, is to eliminate the internal polarizers completely. The idea now is to construct a filter with an entrance and exit polarizer but no others. Such a filter is known as a Solc filter, or a lossless filter, and was first described by Ivan Solc (1954). The potential gain is dramatic as now such a filter would have a transmission of 40% in unpolarized light.
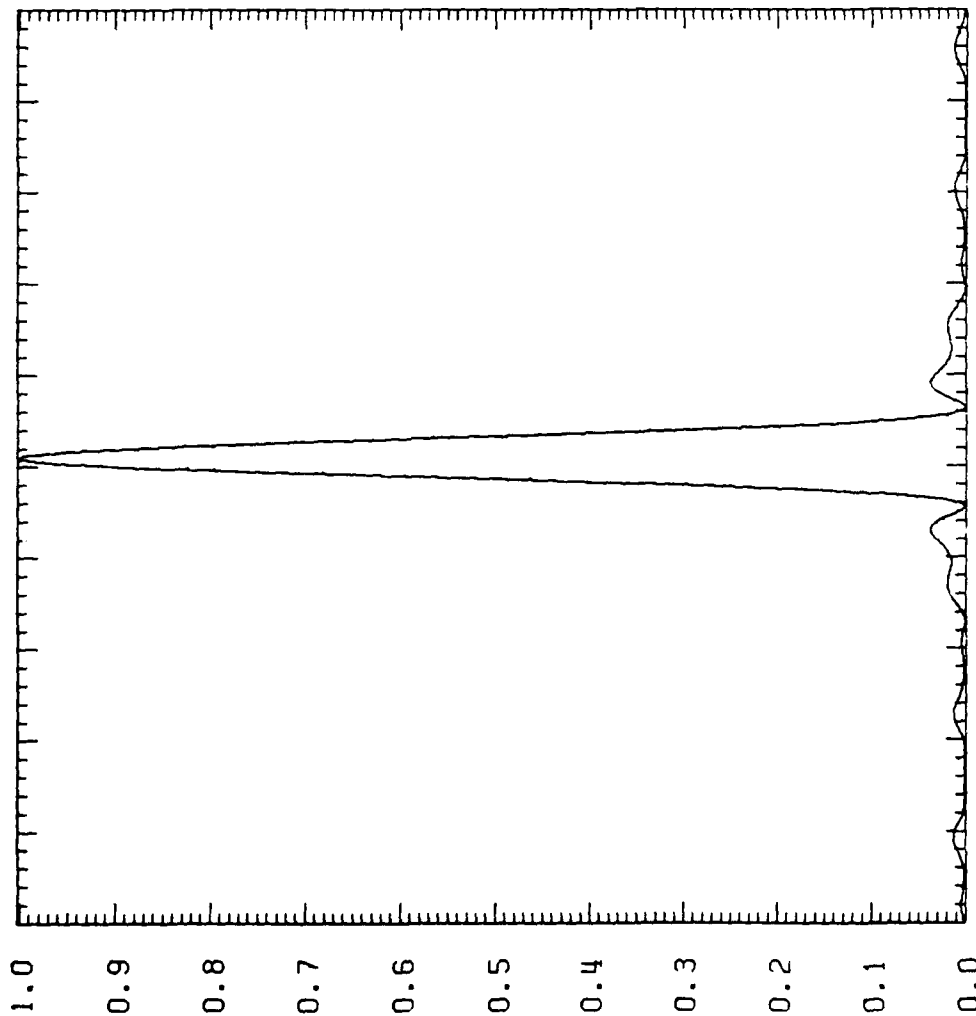
The problem is that in order to realize a Solc filter it has taken an unmanageable number of thin elements. Whereas the Lyot design can be looked at as the minimum number of elements needed to realize a narrowband filter, the Solc design is the maximum number. This has made construction of these filters an extremely demanding optical task. Only a few have actually been built and none have approached their potential. Large sidelobes and reduced transmission have been typical of Solc assemblies. Moreover, the assembly process has been a matter of trial and error since intermediate stages in the construction do not act like filters themselves.

In 1964, Harris, et al., formulated a mathematical theory of general lossless filters of which Solc's original designs are a particularly clever special case. Unfortunately, while they established a basis for design of lossless filters, they did not address any aspect of practicality. During this study we examined the Harris formalism and wrote a general lossless filter synthesis computer program. Through persistent use of the program, some common-sense approaches and quite a bit of good luck, we discovered a new class of lossless filter designs which have important advantages for practical construction. These designs, like all lossless filters, have no internal polarizers so they have the potential for very high transmission. Unlike other lossless filter designs they are economical in terms of the number of distinct elements. Additionally, they have a central core which can be assembled and tested separately.

A forthcoming paper by Title and Rosenberg will present the mathematical basis for these filter designs, so the presentation here will be brief and will only present the construction principle.

Standard Solc filters come in two types, the fan filter and the folded filter. They are equivalent but not identical, and the fan filter is the form in which we are interested. In a fan filter a number, n, of identical birefringent crystal elements are arranged with monotonically increasing orientation angle of their optic axes. The result looks much like a number of playing cards fanned out. In Solc's original discussion, the inter crystal angles were all identical and divided 90° by n. As has been shown, subsequently small modifications of these angles can change the sidelobe structure of the filter and improve its performance. In general, it is not too difficult to construct such a filter with a modest, n equal 6 to 10, number of plates. As n grows larger, the interplate angles grow smaller and the orientation errors become more important. For filters with 20 or more plates the assembly becomes very critical.

The advance during this study was to note that a fan filter could be sandwiched between two thick plates to improve the performance of the filter. Specifically, an n plate fan filter may be sandwiched between two plates, each of thickness equal to the n plates, to produce a narrowband filter equivalent to a fan filter with 3n plates. Thus, for example, a 7-element lossless filter may be assembled which has the same transmission spectrum as a 15-element fan filter.

FILTER DESIGN

INC.	POL. - LINEAR	0.0 DEG.	
P 0:	0.00	L: 0.000	T: 1.000
R 0:	2.04	T: 1.000	B:QUARTZ
R 0:	4.42	T: 1.000	B:QUARTZ
R 0:	8.08	T: 1.000	B:QUARTZ
R 0:	13.42	T: 1.000	B:QUARTZ
R 0:	20.95	T: 1.000	B:QUARTZ
R 0:	30.79	T: 1.000	B:QUARTZ
R 0:	37.85	T: 1.000	B:QUARTZ
R 0:	45.00	T: 1.000	B:QUARTZ
R 0:	52.15	T: 1.000	B:QUARTZ
R 0:	59.21	T: 1.000	B:QUARTZ
R 0:	69.05	T: 1.000	B:QUARTZ
R 0:	76.58	T: 1.000	B:QUARTZ
R 0:	81.92	T: 1.000	B:QUARTZ
R 0:	85.58	T: 1.000	B:QUARTZ
R 0:	87.96	T: 1.000	B:QUARTZ
P 0:	0.00	L: 0.000	T: 1.000

FILTER DESIGN

INC.	POL. - LINEAR	0.0 DEG.	
P 0:	0.00	L: 0.000	T: 1.000
R 0:	76.25	T: 5.000	B:QUARTZ
R 0:	10.50	T: 1.000	B:QUARTZ
R 0:	26.75	T: 1.000	B:QUARTZ
R 0:	45.00	T: 1.000	B:QUARTZ
R 0:	63.25	T: 1.000	B:QUARTZ
R 0:	79.50	T: 1.000	B:QUARTZ
R 0:	13.75	T: 5.000	B:QUARTZ
P 0:	0.00	L: 0.000	T: 1.000

5200 5240 5280 5320 5360 5400 5440 5480 5520 5560 5600

1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0

Moreover the central 5 elements form a narrowband fan filter and may be assembled and tested separately. The plate orientation angles and transmission spectrum of such a combination is shown below. While the scope of this project did not allow for construction and testing of filters like these, we believe that they will prove to be very practical.

Though we have used a 15-element filter as an example, the effect is more general. Any length fan filter may be used as the central core as long as it is bracketed by single elements, each of whose lengths equals that of the core.

V. SLCAIR 81

An unexpected bonus in this project came in the fall of 1980 when it was decided to organize an SLC demonstration in the spring of 1981. In order to permit daylight operation of the GTE-Sylvania optical receiver, a blue-green narrowband filter was required. Consequently, the funding and scope of this project was extended to allow for construction of such a filter. The filter was to have a 2Å bandpass centered at λ5320.7 when operated at 35°C. Since it was to be operated with a multilayer dielectric interference blocking filter, it needed to have a free spectral range of 200Å.

In the interest of schedule we chose to build the most straightforward filter possible. This turned out to be a 7-element Lyot filter. We had a tunable quartz filter which we had built several years previously. It had a 7.5-cm aperture and a 20Å bandwidth. From it we borrowed the four thickest elements. Since they were already assembled as tuning elements with their quarter wave plates, it was no problem transferring them to the new filter.

For the narrowband end we used a quartz crystal from Sawyer Research. As it was more than 10 cm in width, we chose to make 10-cm plates. This may seem strange to have one end of the filter be larger than the other but it is better than to have all the plates small. As we normally do, we made the three thick elements tunable also. We assembled the entire filter in our lab at nominal room temperature having previously calculated the shift to be expected. A spectral trace is shown below. Notice the Fraunhofer absorption lines superimposed on the spectrum. These are a result of using sunlight as the illumination source. It provides an absolute wavelength calibration to the spectrometer.

VI. NON-VIGNETTING

The primary goal of this project was to develop large aperture, wide-field-of-view, birefringent filters. We already knew how to field widen uniaxial crystal elements so the main challenge was to construct large-aperture elements. Since this is a non-imaging application, there is actually no specific need for the large aperture to consist of only one segment. A large effective aperture could just as well be assembled from many smaller subapertures. The flaw is that for a quartz narrowband filter, many of the off-axis rays would be vignetted by the sides of the filter.

At one point we considered polishing the sides of square or hexagonal elements and optically contacting segments to increase the aperture. This is unfeasible and would probably have failed. Finally, however, another solution was found which eliminates the vignetting loss while allowing the combination of

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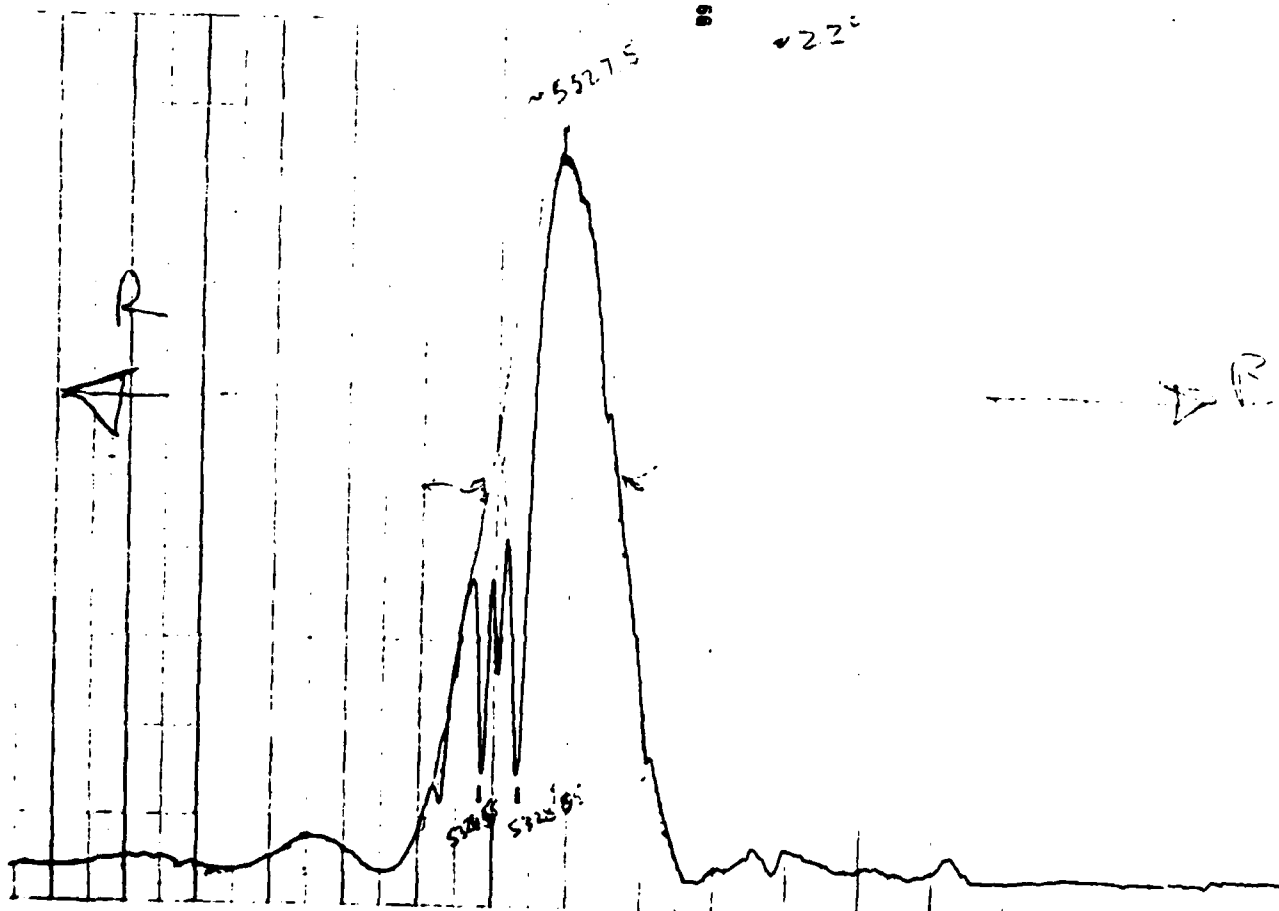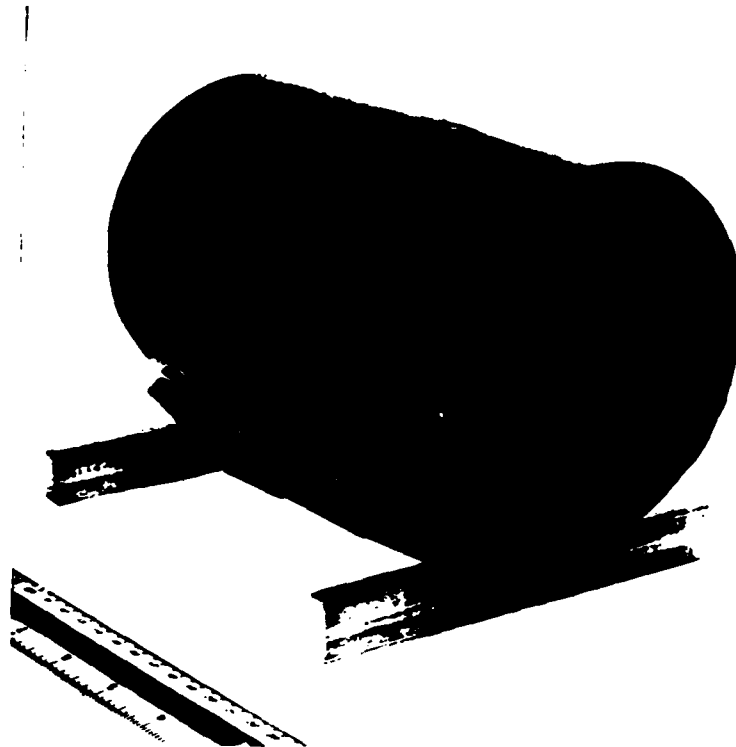
smaller subapertures into a larger effective aperture. The solution is to let the extreme rays reflect internally off the walls and stay inside the filter.

Usually when a ray is totally internally reflected in a crystal element, two problems arise. First, depending upon the angle the ray makes with the wall, the azimuth of the ray is changed. While a wide field element, as a whole, is azimuth insensitive, each crystal section is extremely azimuth sensitive. Any azimuthal deviation by a ray can, therefore, completely change the transmission spectrum of the effective filter which it sees. The remedy is to cut the crystal plates in such a way so as to exploit the mirror symmetry planes. This means cutting square elements in which the sides are, respectively, parallel and perpendicular to the optic axis of the plate. Since the crystal has mirror symmetry parallel and perpendicular to the optic axis, reflections are spectrally indistinguishable from the incident rays. Thus the first objection is overcome.

The second problem is more subtle and its solution is not exact but only a very close approximation. As rays are totally internally reflected, their s and p polarizations undergo different phase shifts. This means that there will be a differential phase shift which is equivalent to additional birefringent path length. Again, this would change the spectral transmission for the reflected rays unacceptably. Fortunately, there is a simple solution. It is known that there are two incident angles at which the differential phase shift is zero. These are grazing incidence, corresponding to on-axis rays in the filter, and rays incident exactly at the critical angle. Now, normally in quartz, the critical angle for total internal reflection is moderately large. It is so large, in fact, that it is impossible for a ray which enters the top of the filter to avoid being reflected back into the filter. Only by changing the outer index of refraction can the rays be forced to leave the crystal. The idea, then, is to coat the outside of the quartz crystals with a material such that rays within the filter's field of view are totally internally reflected if they strike the walls, while rays outside of the field of view pass through and are absorbed outside of the filter. The index of refraction to achieve this is given by

$$n_c = (n_Q^2 - \sin^2\theta)^{1/2}$$

where n_c is the index of refraction of the coating, n_Q, is the index of refraction of the crystal quartz, and θ is the extreme external field half angle. For a field angle of approximately $24°$, the coating should have an index of 1.51. At this angle, as well as on-axis, there is no differential phase shift. How much can there be in between? For these conditions, there can be a maximum of $3°$ differential phase shift which corresponds to a filter spectral shift of 1.6% of the bandwidth. For a 2Å filter this would correspond to 32 milliAngstroms, which is negligible.
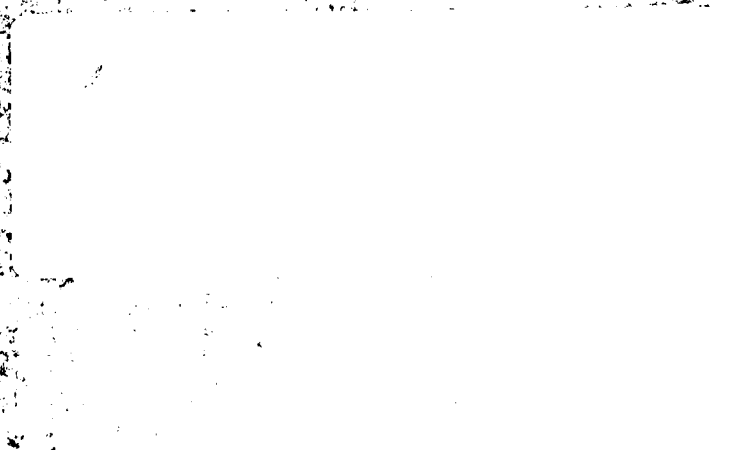
The technique, then, involves building a square filter in which the optic axis of each plate is parallel to a side of its plate. Then, after polishing the sides as well as the top and bottom, the sides must be coated with the appropriate index material followed by an absorber. The gain is that now a collection of small apertures is equivalent to a large aperture.

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